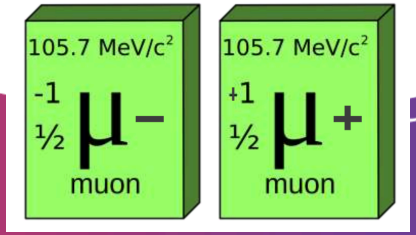
Muon Collider Studies

E. Métral (many thanks to D. Schulte and all IMCC colleagues)

International MUON Collider Collaboration

CERN

$$m_\mu = 105.7\ MeV/c^2$$
$$\tau_\mu = 2.2\ \mu s$$



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- Introduction
- Overview: Novelties, challenges, etc.
- Expected contributions from ABP and ABP-CEI
- Timelines and milestones
- Conclusion and next steps

Introduction

- Muon colliders have a great potential for high-energy physics. They can offer **collisions of point-like particles** at very high energies, since muons can be accelerated in a ring **without limitation from synchrotron radiation**

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- However, the need for high luminosity faces technical challenges which arise from the **short muon lifetime at rest** and the **difficulty of producing large numbers of muons in bunches with small emittance**

- Addressing these challenges requires the development of **innovative concepts and demanding technologies**

Introduction

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- In response to this, the Laboratory Directors Group (**LDG**), which represents the large European Particle Physics Laboratories has initiated an **International Muon Collider Collaboration** to study the concept

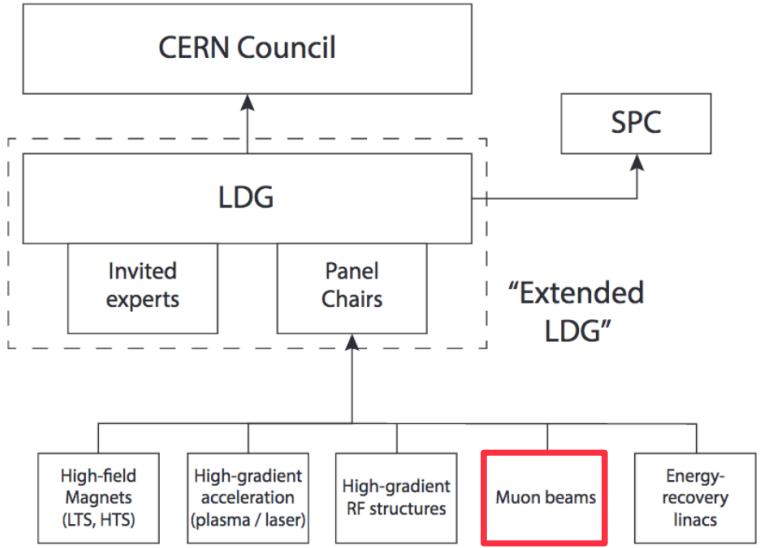
Introduction

European Accelerator R&D Roadmap

LDG: directors of the largest European Laboratories

Panels

- Magnets: P. Vedrine
- Plasma: R. Assmann
- RF: S. Bousson
- Muons: D. Schulte
- ERL: M. Klein



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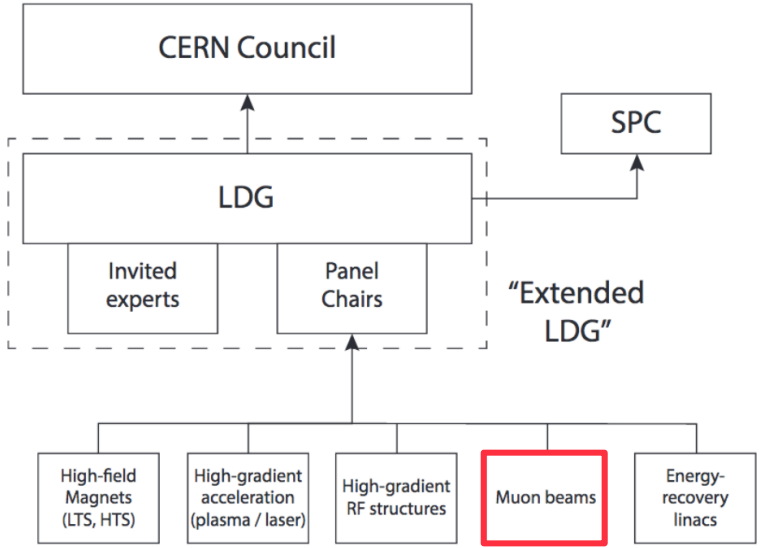
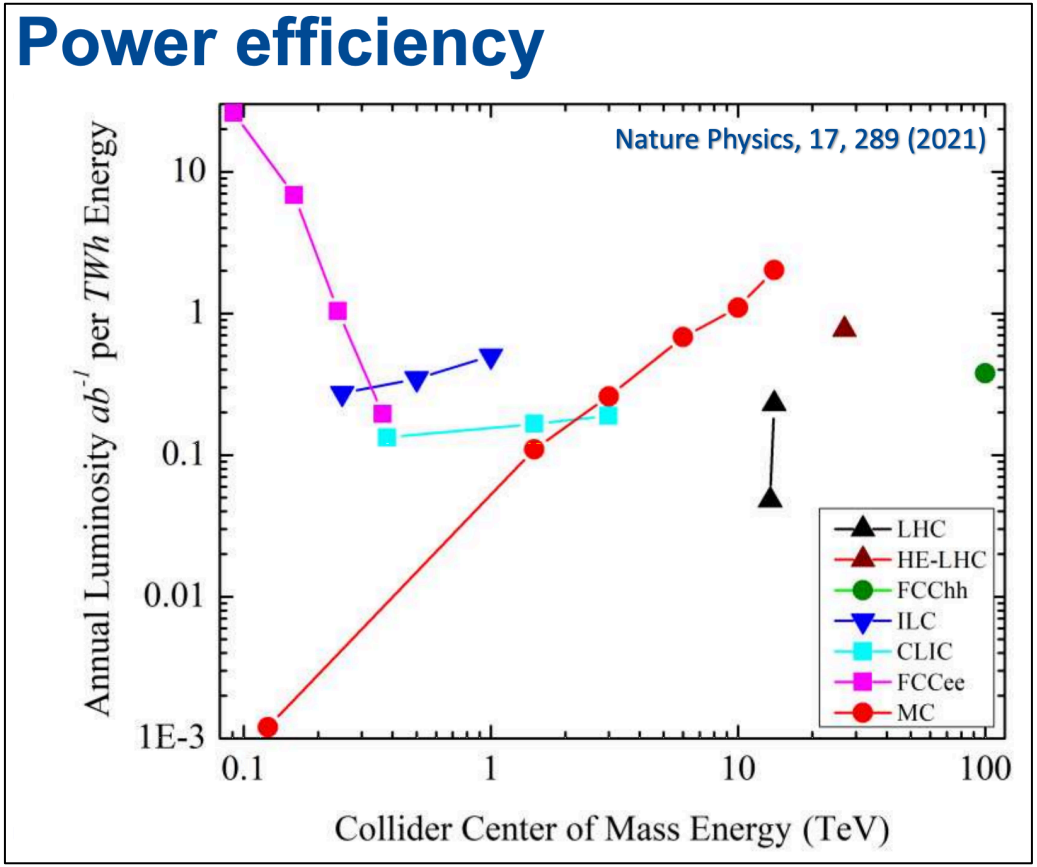


N. Mounet is a LDG Scientific Secretary

Introduction

Power efficiency



Introduction

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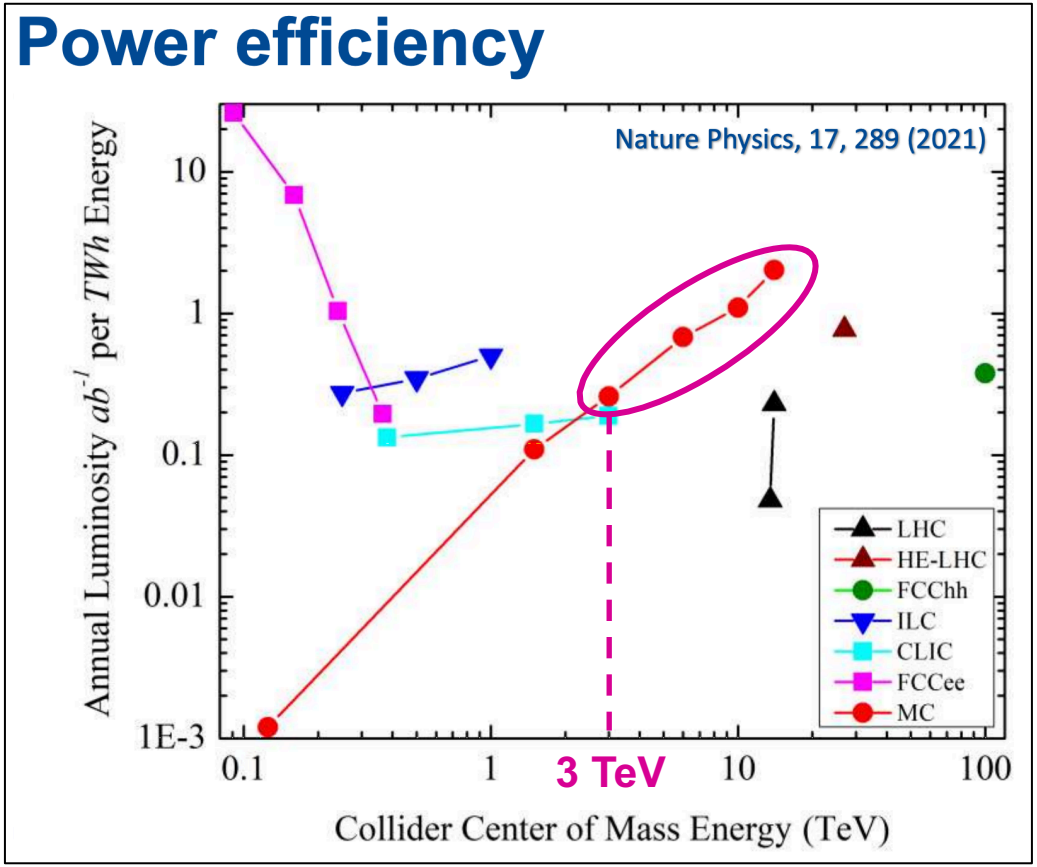
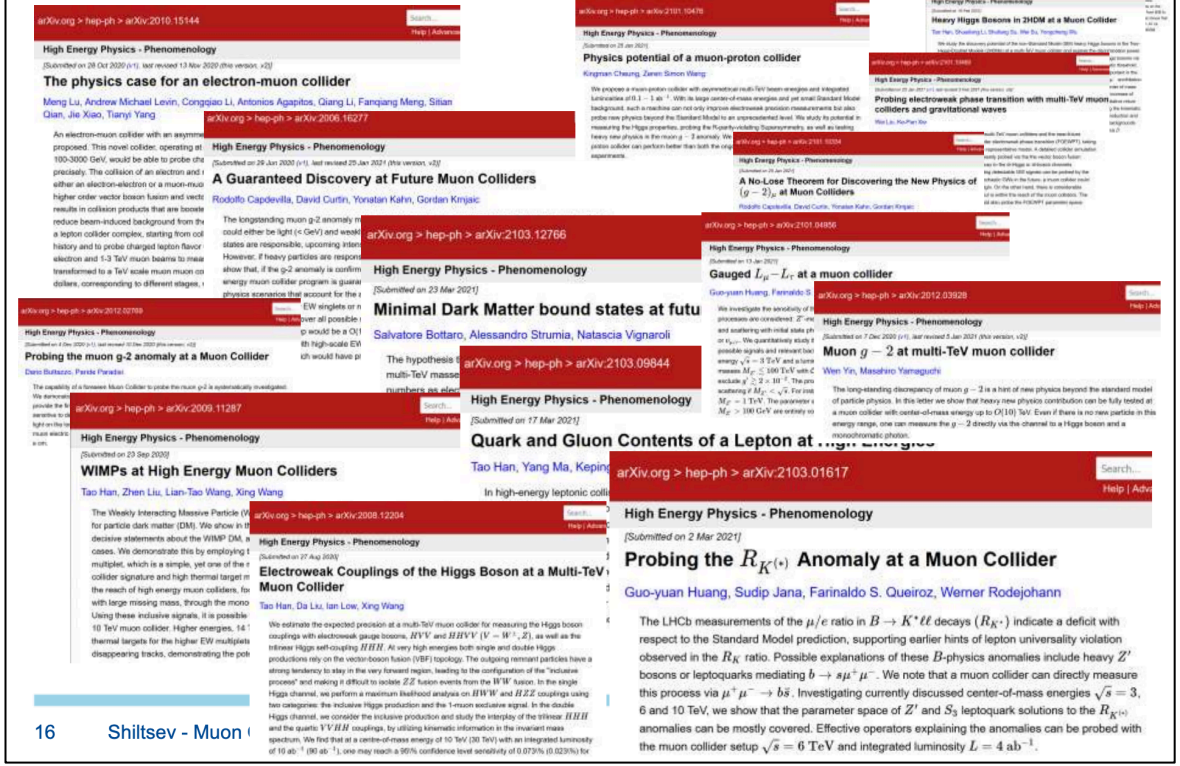


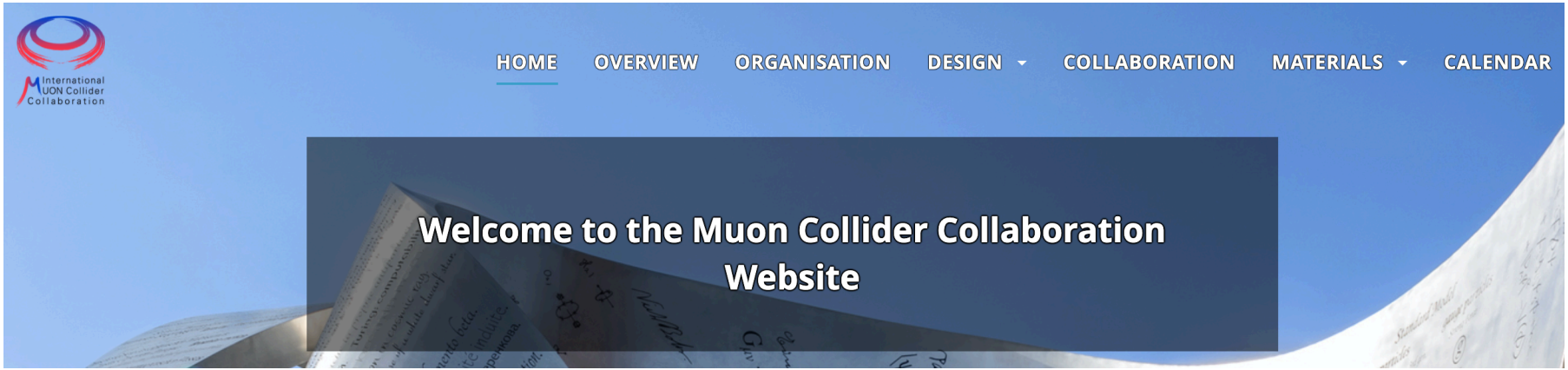
Introduction

Physics Case (2020-21 “explosion”)



Webpage of the IMCC

https://muoncollider.web.cern.ch/welcome-page-muon-collider-website



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- It will provide a **baseline concept**, well-supported performance expectations and assess the **associated key risks as well as cost and power consumption drivers**
- It will also identify an **R&D path to demonstrate the feasibility of the collider**

Organisation of the IMCC
(https://muoncollider.web.cern.ch/organisation)

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MUON BEAM PANEL

Meetings during CEI section meeting slot (every other week)

0) Integration, project, reserve: Daniel Schulte (CERN) and Mark Palmer (BNL).

1) Muon production and cooling: Chris Rogers (STFC-RAL) and Diktys Stratakis (FNAL).

2) Muon acceleration and collision: Antoine Chance (IRFU) and Angeles Faus-Golfe (IJClab).

3) Magnets: Lionel Quettier (IRFU) and Tabea Arndt (KIT).

4) RF: Jean-Pierre Delahaye (CERN retiree) and Akira Yamamoto (CERN/KEK).

5) Particle-matter interaction: Simone Gilardoni (CERN) and Nadia Pastrone (INFN-Torino).

6) Beam dynamics: Tor Raubenheimer (SLAC/Stanford University) and Elias Metral (CERN).

7) Other systems and issues: Philippe Lebrun (European Scientific Institute) and Mike Seidel (EPFL/PSI).

8) Other muon beam opportunities: Ken Long (Imperial College London).

9) LEMMA: Nadia Pastrone (INFN-Torino) and Angeles Faus-Golfe (IJClab).

Organisation of the IMCC
(https://muoncollider.web.cern.ch/organisation)

CONTACT PEOPLE

Role:

- They should help the panel to do its duty.
- They should dispatch questions to relevant experts.
- They are responsible for ensuring that an answer is provided.

List for Design

- ***Parameters***: Daniel Schulte.
- ***High-energy complex***: Alex Bogacz (linacs), Shinji Machida (FFA), Antoine Chance (RCS), Christian Carli (collider), Anton Lechner (shielding).
  - ***Muon production and cooling***: Chris Rogers, Marco Caviani, Chris Densham.
  - ***Proton complex***: Ilias Efthymiopoulos, Frank Gerigk.
  - ***Test facility***: Roberto Losito.
  - ***Beam Dynamics***: Elias Metral.
  - ***LEMMA***: Marica Biagini.

List for Technologies and Infrastructure

- ***RF***: Alexej Grudiev.
- ***Magnets***: Lionel Quettier.
- ***Power converter***: Davide Aguglia, Fulvio Boattini.
- ***Beam instrumentation***: Manfred Wendt.
- ***Vacuum***: Jose Antonio Ferreira Somoza.
- ***Alignment***: Helene Mainaud-Durand.
- ***Cryogenics***: Rob van Weelderen, Patricia Tavares Coutinho Borges De Sousa.
- ***MDI***: Donatella Lucchesi (MDI), Anton Lechner (shielding/MDI), Christian Carli.
- ***Radiation protection***: Claudia Ahdida, Markus Widorski.
- ***Civil engineering***: John Osborne, Youri Robert.

Organisation of the IMCC
(https://muoncollider.web.cern.ch/organisation)

CONVENERS OF THE 11 WORKING GROUPS (note that we are in the process of enhancing the working group conveners, so the following is subject to change: as of 15/06/21)

Radio-Frequency (RF): Alexej Grudiev, Jean-Pierre Delahaye, Derun Li, Akira Yamamoto.

Magnets: Lionel Quettier, Toru Ogitsu, Soren Prestemon, Sasha Zlobin.

High-Energy Complex (HEC): Antoine Chance, J. Scott Berg, Alex Bogacz, Christian Carli, Angeles Faus-Golfe, Eliana Gianfelice-Wendt, Shinji Machida.

Muon Production and Cooling (MPC): Chris Rogers, Marco Calviani, Chris Densham, Diktys Stratakis, Akira Sato, Katsuya Yonehara.

Proton Complex (PC): Simone Gilardoni, Frank Gerigk, Natalia Milas.

Beam Dynamics (BD): Elias Metral, Tor Raubenheimer, Rob Ryne.

Radiation Protection (RP): Claudia Ahdida.

Parameters, Power and Cost (PPC): Daniel Schulte, Mark Palmer, Philippe Lebrun, Mike Seidel, Vladimir Shiltsev, Jingyu Tang.

Machine Detector Interface (MDI): Donatella Lucchesi, Christian Carli, Anton Lechner, Nicolai Mokhov, Nadia Pastrone.

Synergy: Kenneth Long, Roger Ruber.

Test Facility (TF): Roberto Losito, Alan Bross, Tord Ekelof.

Organisation of the IMCC
(https://muoncollider.web.cern.ch/organisation)

- **Accelerator Design Meetings** chaired by Daniel on Monday afternoons (16:00-18:00)

- **Beam Dynamics meetings** chaired by me usually on Wednesday afternoons (anybody can subscribe to **e-group: muoncollider-bd**)

  => Beam Dynamics meeting #7 yesterday

  => See indico sites: https://indico.cern.ch/category/12762/

- Other Working Groups have also their own meetings

Organisation of the IMCC
(https://muoncollider.web.cern.ch/organisation)

https://indico.cern.ch/event/1030726/

1st Muon Community Meeting

20-21 May 2021
Zoom
Europe/Zurich timezone

https://indico.cern.ch/event/1043242/

2nd Muon Community Meeting

12-14 July 2021
Zoom
Europe/Zurich timezone

=> See more info on Calendar: https://muoncollider.web.cern.ch/events-calendar

https://indico.cern.ch/event/1016248/

Workshop on Muon Collider Testing Opportunities

24-25 March 2021
Europe/Zurich timezone

Overview: Novelties, challenges, etc.

Idea

Protons → target

→ pions

→ muons

→ μ- μ+ collider

International MUON Collider Collaboration

Idea

Protons → target

→ pions

→ muons

→ μ^- μ^+ collider

Challenges (of decaying particles)

- Muon production
- Fast muon cooling
- Fast acceleration
- Neutrino radiation

International MUON Collider Collaboration

Published: 28 July 1977

Measurements of relativistic time dilatation for positive and negative muons in a circular orbit

J. Bailey, K. Borer, F. Combley, H. Drumm, F. Krienen, F. Lange, E. Picasso, W. von Ruden, F. J. M. Farley, J. H. Field, W. Flegel & P. M. Hattersley

Nature **268**, 301–305 (1977) | Cite this article

596 Accesses | **153** Citations | **19** Altmetric | Metrics

Abstract

The lifetimes of both positive and negative relativistic ($\gamma = 29.33$) muons have been measured in the CERN Muon Storage Ring with the results $\tau^+ = 64.419\ (58)\ \mu s$, $\tau^- = 64.368\ (29)\ \mu s$ The value for positive muons is in accordance with special relativity and the measured lifetime at rest: the Einstein time dilation factor agrees with experiment with a fractional error of 2×10^{-3} at 95% confidence. Assuming special relativity, the mean proper lifetime for μ^- is found to be $\tau_0^- = 2.1948(10)\ \mu s$ the most accurate value reported to date. The agreement of this value with previously measured values of τ_0^+ confirms CPT invariance for the weak interaction in muon decay.

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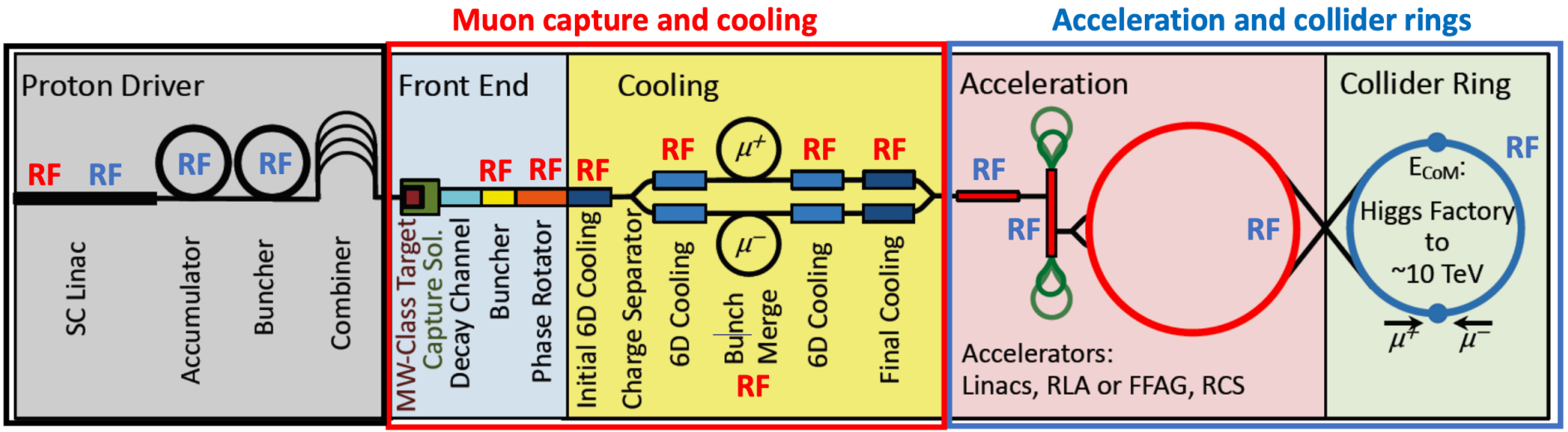
$$\tau = \gamma\, \tau_0$$

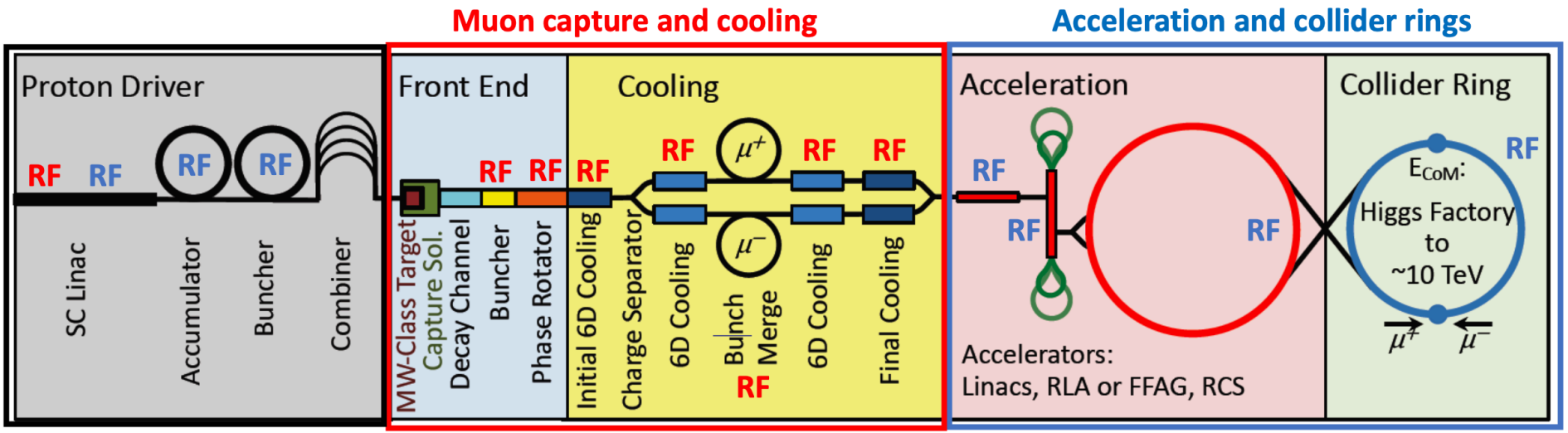
~ 150 ms at 7 TeV

Challenges at all stages!



Challenges at all stages!

Ionisation cooling in matter (due to short time scale)



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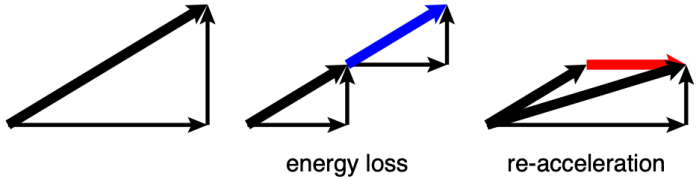
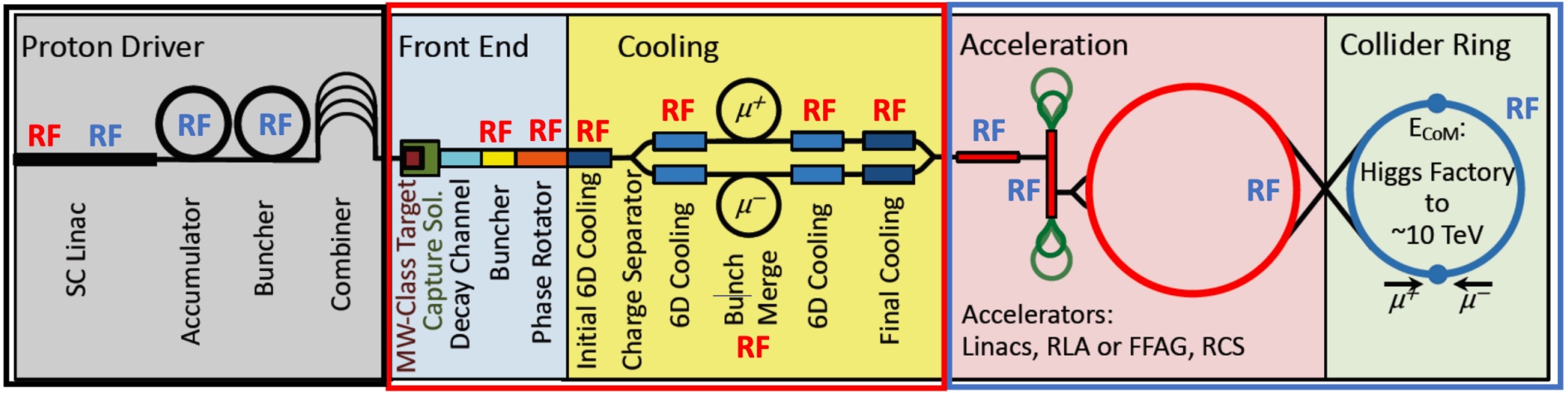
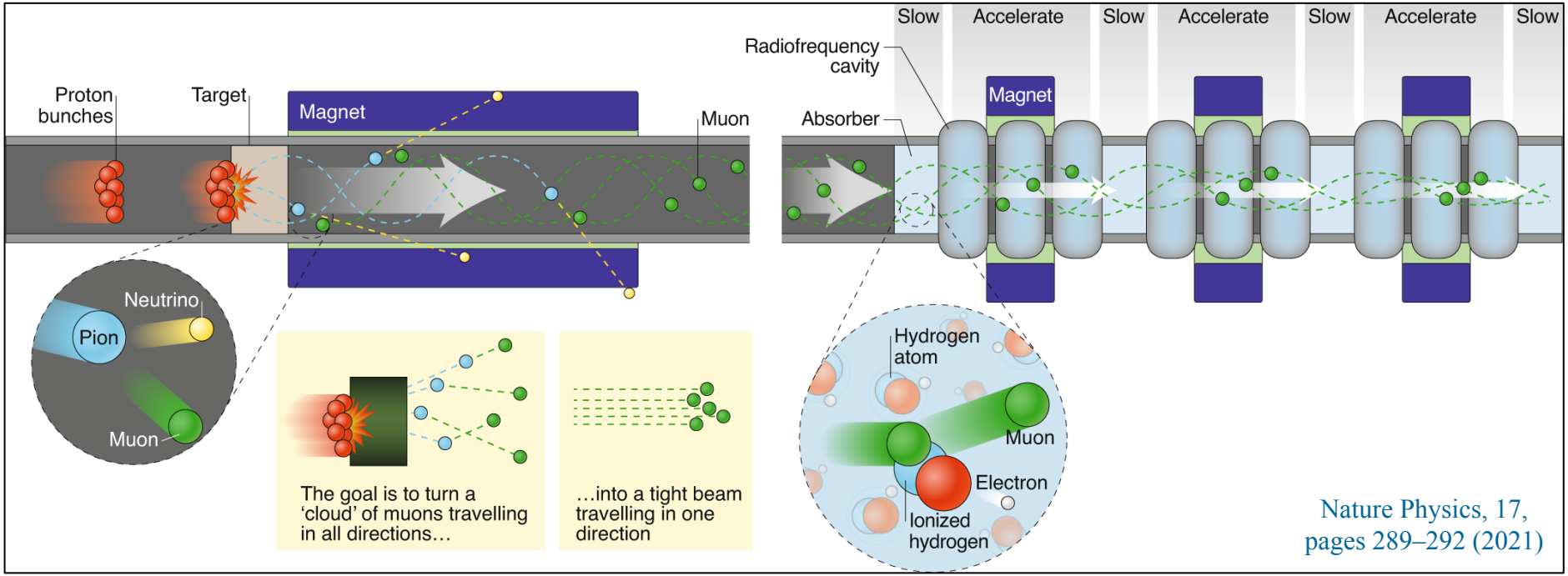


Muon capture and cooling

Acceleration and collider rings

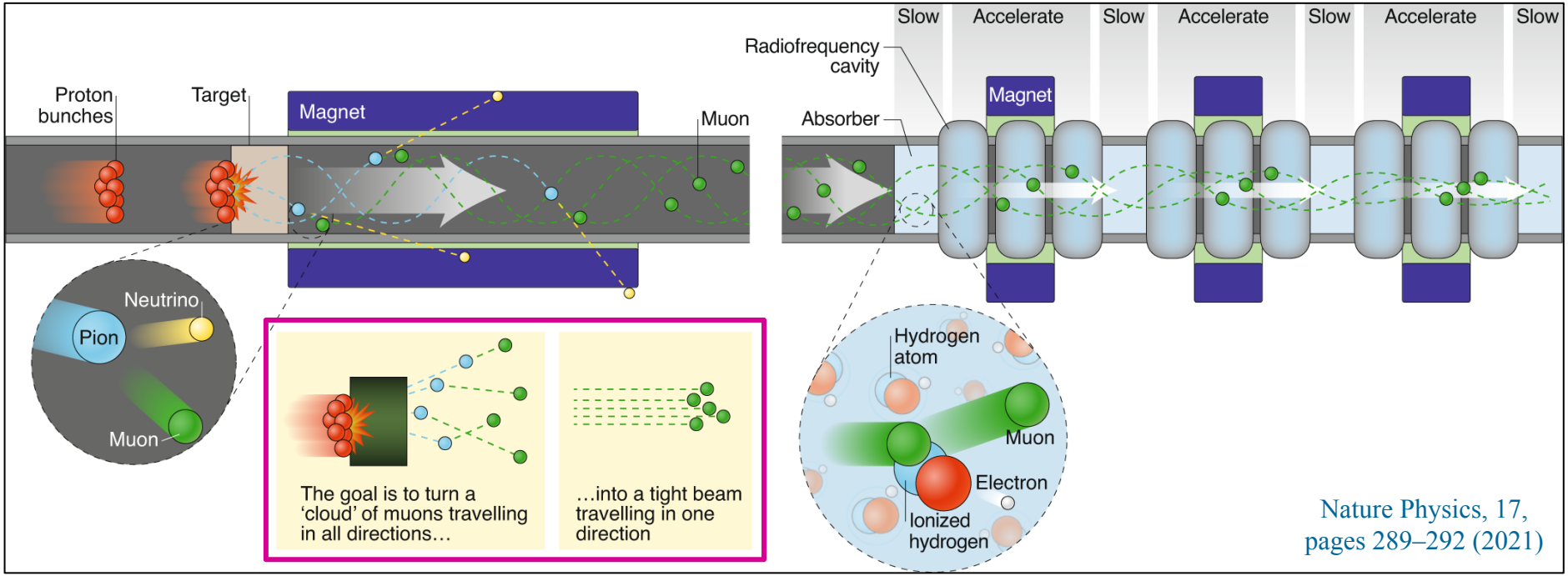


Muon production



Nature Physics, 17, pages 289–292 (2021)

Muon production



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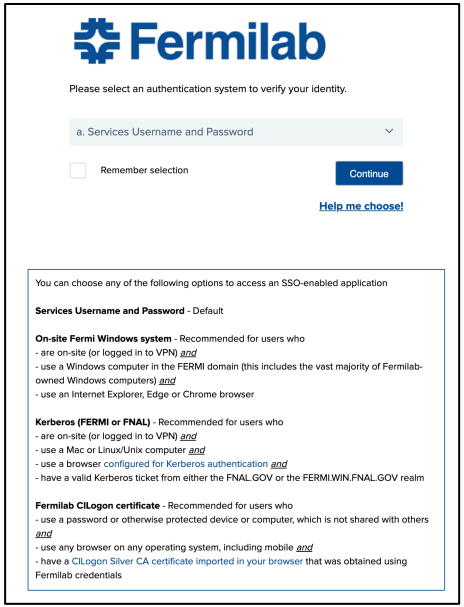
MAP = US Muon Accelerator Program (2010-2017) led by Mark Palmer

- MAP webpage: https://map.fnal.gov/
- Remark: it is not possible to access it anymore since few weeks, hoping that the problem will be fixed soon



Vladimir Shiltsev (29/03/21)

International MUON Collider Collaboration

Steps Toward Muon Collider

- MICE observed cooling (2018)
- European Strategy endorsed MC R&D (2020)
- Since then - in Europe:
  - CERN 2M$/yr, MuonCollCollaboration
  - Test facility design(2025) & construction (2031) & operation
  - Muon Collider design(2031) and start of construction (2037)
- Since then - in the US:
  - Snowmass'21 great interest (EF, TF, AF)
  - Muon Collider Forum (APS APR'21 four mini-symposia)
    - Fermilab "Collider Group" established (P.Bhat, S.Jindariani, et al)
- We should not repeat past mistakes:
  - make *"physics first"* and augment it with accelerator effort
  - We should strive for the Snowmass'21 outcome –

Muon Collider Physics R&D and Design work should become part of the 2023 P5 plan

48 Shiltsev Fermilab

https://indico.cern.ch/event/1022802/contributions/4293870/attachments/2218112/3755618/MuonCollider_UChi_03292021_v1.pdf

Energy and luminosity goals for the IMCC

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Reasonably conservative
- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

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σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63
Muon lifetime	[turn]	2078	3117	3117

D. Schulte Muon Collider, March 23, 2021 14

Tentative IMC 3 TeV
(based on MAP potential transmission factors)

IMC	3 TeV	Particle Transmission		Dilution/Cooling Factor: Transverse emittances		Dilution/Cooling Factor: Longitudinal emittances		Beam Energy	Number of bunches	Particles per bunch	Norm transv emittance	Norm. long. emittance	Bunch length	Beam Power
5	Rep rate (Hz)							GeV	#	E12	μrad-m	mrad-m	mm	W
	Driver	0.153 at 8GeV						5	1	376.89			600 (2ns)	1.5E+06
Target & Front End		0.0956						0.255	12	36.04	15000	45	85.2	8.8E+04
Cooling	Initial Cooling	0.72	0.108	0.2	0.003	0.22	2.182	0.255	12	25.77	3000	10	85.2	6.3E+04
	Charge separator	0.90		1.05		1.05		0.255	12	23.19	3150	10	85.2	5.7E+04
	6D cooling before merge	0.72		0.5		0.20		0.255	12	16.58	1575	2	85.2	4.1E+04
	6D merge	0.88		2		4.00		0.255	1	14.59	3150	8	92.3	3.0E+03
	6D cooling after merge	0.44		0.067		0.23		0.255	1	6.42	211	2	92.3	1.3E+03
	Final cooling & Re-Accel	0.61		0.188		52.00		0.255	1	3.91	40	98	92.3	8.0E+02
Acceleration	Injector Linac	0.92	0.568	1.05	1.159	1.05	1.159	1.25	1	3.60	42	103	46.2	3.6E+03
	RLA1	0.92		1.02		1.02		5	1	3.32	42	105	23.1	1.3E+04
	RLA2	0.85		1.02		1.02		62.5	1	2.83	43	107	23.1	1.4E+05
	RCS1	0.90		1.02		1.02		303	1	2.54	44	109	23.1	6.2E+05
	RCS2	0.92		1.02		1.02		750	1	2.34	45	112	23.1	1.4E+06
	RCS3	0.95		1.02		1.02		1500	1	2.22	46	114	23.1	2.7E+06
Collider	IP	0.99		1.02		1.02		1500	1	2.20	47	116	5.0	2.6E+06
Front End to IP		6.10E-02		3.12E-03		2.58								

Proton beam power on target for 2.2E12 μ /5Hz at IP: 1.5 MW

IP transverse/longitudinal emittances: 47/116 mm-mrad

J.P.Delahaye

2

Conclusion

- **MAP R&D results provide a potential for significative improvements.**
  - Transmission efficiency up to 6% from Front-End to IP
  - Transverse emittances at IP reduced to 0.3% of the one at Front End
- **Applying the MAP potential figures to IMC would lead to:**
  - A beam power on target of 1.5MW for nominal charge/b at IP
  - Transverse emittance 1.9 larger than specified: 47 vs 25 μm
  - Longitudinal emittance 1.6 larger than specified: 116mm vs 70mm
  - Potential Luminosity reduction by a factor 2 to 3
  - IMC 10TeV: additional RCS(?), 90%(?) transmission, 2E12/b(?) at IP
- Informed & tentative starting point to launch IMC reflection

J.P.Delahaye

3

List of R&D items for Beam Dynamics

Summary of the challenges for the Beam Dynamics Working Group

Conveners: R. Ryne, T. Raubenheimer and E. Métral

Even if everything needs to be done quickly with muons (due to the short lifetime), many issues can happen with high bunch charges and high impedances (which is the case here with the many RF stations all along the muon collider chain) and many aspects need to be carefully studied. The BD-WG identified and prioritized 12 R&D items (many thanks to all participants, MAP experts, Daniel and Mark):

Criticality 1 (high):

1) New beam dynamics regime during acceleration
2) Opposite sign bunches – beam crossing and wakes
3) Design of the full chain (acceleration in particular)
4) Radiation mitigation by moving the beam / magnets in the collider
5) Collective instabilities during ionization cooling

Criticality 2 (medium):

6) FFAs as an alternative to pulsed synchrotrons
7) Longitudinal and transverse beam dynamics studies in the collider
8) Development of simulation tools

Criticality 3 (low):

9) Halo formation and beam losses in the Proton Driver
10) Check of all cooling studies with a second code
11) Are sextupoles needed in pulsed synchrotrons?
12) Impedance models

List of R&D items for Beam Dynamics

1) is important because the longitudinal and transverse emittances need to be preserved to reach the required collider's luminosity and control the orbit. The issue is that we need to handle 2 high-charge bunches, one of μ^+ and one of μ^-, with a lot of RF (which means a strong longitudinal focusing and a high impedance) and we need to be fast: this is a unique regime for collective dynamics, and the consequences for beam stability and operation (e.g., phase shifting to compensate potential well distortion) need to be understood.

2) is important because both signs of muons are accelerated simultaneously in the rings and linacs. In the rings, there will be 2 beam-beam collision points with wakes in the cavities, which will vary depending on where the cavities are in the ring (cavities must be distributed in several uniformly-spaced stations in the ring). In the linacs, the bunch separation will be too short to allow significant damping of HOMs and compensation of the beam loading. The latter will lead to significant energy or energy spread variation between the bunches. The impact of these collective effects should be understood.

3) is important because right now most of the acceleration designs are conceptual, with few details available. We should start to put together detailed designs and agree on a set of baseline accelerator parameters, which is essential for refined studies (lattices for all stages, from past studies or to be developed/optimized, which should be stored in the versioning CERN repository; RF frequencies; etc.). A particular emphasis should be placed on the longitudinal dynamics since preservation of longitudinal emittance is critical but the transverse plane should not be overlooked.

4) is important as this might be needed to reach acceptable levels of radiation, which is a fundamental aspect of the study. All the consequences for the beam dynamics need to be carefully analysed.

List of R&D items for Beam Dynamics

5) is important because such mechanism could jeopardize the generation of high brightness muon beams through ionization cooling. The knowledge of collective instabilities that could arise from the interaction of the beam with electromagnetic wake fields propagating in matter (absorbers, gas-filled RF cavities, etc.) as well as with the pair of charges generated by ionization is practically non-existing.

6) is important because particularly at lower energies, driving the magnets requires very rapid ramp rates. The challenges associated with this may drive us towards alternatives, in particular FFAs. For example, the vFFA is a relatively new concept with unique coupled optics and a great importance of fringe fields, no machine was constructed yet and there are no dedicated tools to study collective effects.

7) is important because we need to operate the collider close to the isochronous condition in order to use a reasonable RF voltage, which means that there will be no help from a high synchrotron tune for beam instabilities (both longitudinal and transverse). The significance of the single-particle effects (resonances, working point, β-beating, …) vs. the short muon lifetime need also to be assessed.

8) is important because we need to have a detailed understanding of the many challenging mechanisms and new regimes: the collective beam-matter interactions need to be studied; non-standard acceleration schemes need to be developed; tools to study collective effects for vFFA for instance need to be developed; what about the study of the muon losses (we cannot collimate because muons go through everything and the issue is the decay products…)? Etc.

List of R&D items for Beam Dynamics

9) is important because the more protons (and therefore the more muons we create), the easier it is afterwards. The issue is that we need a high (few MW) beam power, with a short (1-2 ns) bunch length and in particular a low (5 Hz) repetition rate.

10) is important because cooling it the key ingredient for a muon collider, and therefore it has to be fully understood and optimized. One should not rely on only 1 code (ICOOL, for which the most complete simulation studies were made) and use G4BL and/or G4MICE to check all the past results (e.g. ICOOL does not do hadronic interactions).

11) is important because in an ordinary synchrotron, it would be important to correct the chromaticity to mitigate the head-tail instabilities. Is that needed in our operating regime? It would be preferable to avoid sextupoles to maintain a high dipole packing fraction and avoid feed-down since the beam will likely have to move in the sextupoles during the ramp.

12) is important because building a realistic impedance model of a machine is a necessary step to be able to evaluate the machine performance limitations, identify the main contributors in case an impedance reduction is required, and study the interaction with other mechanisms such as optics nonlinearities, transverse damper, noise, space charge, electron cloud, beam-beam (in a collider) … It requires time and resources, with many interactions with the equipment groups and here the impedance of many machines need be built. However, the impedance from RF and the resistive-wall impedance dominate the cooling and the acceleration stages and therefore, there, it could be quickly done.

Expected contributions from ABP and ABP-CEI

- **Optics repository** => Talk at the Joint NDC-LNO meeting on 09/06/2021 (https://indico.cern.ch/event/1047287/contributions/4399564/attachments/2260648/3837325/OpticsRepositoryForMuonStudy_EM_09-06-21.pdf) to propose to use the CERN optics GitLab repository

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- **Impedance repository** => Would this be also possible?
- **Need to identify people to work, supervise, steer, etc. in particular for the 5 most critical aspects**
  - Xavier and possible students to work on items 2) and 5)?
  - Ongoing discussions with other teams at CERN and elsewhere

Timelines and milestones => See Calendar: https://muoncollider.web.cern.ch/events-calendar

- A **first short (few pages) report** on identified R&D list has been sent by Daniel to LDG, as foreseen at the beginning of June

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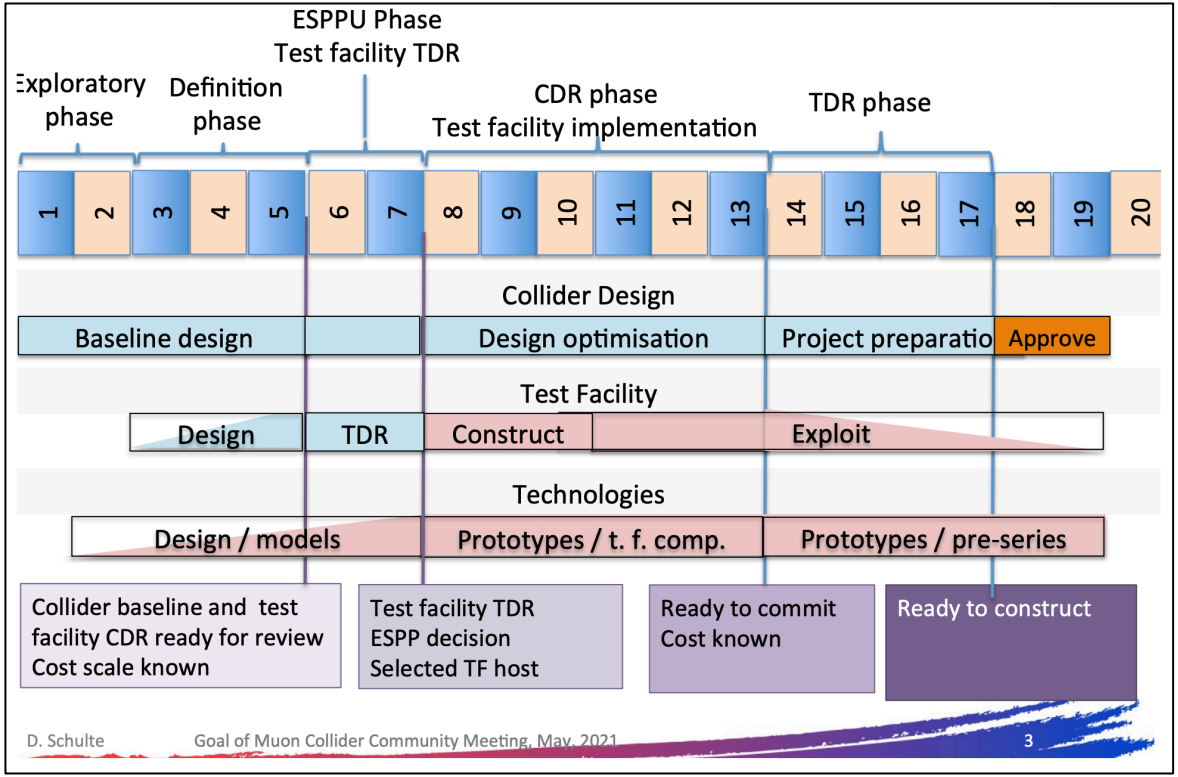
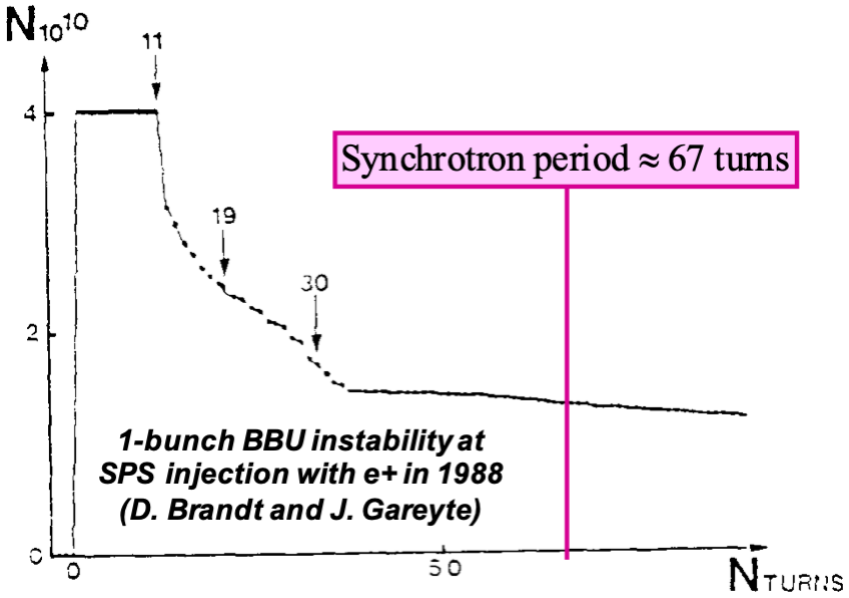
- From 06/12/21 to 07/12/21: SPC / Council => **LDG provides final report (to be written before!) to Council (hoping to gain approval)**

Timelines and milestones => See Calendar: https://muoncollider.web.cern.ch/events-calendar



Conclusion and next steps



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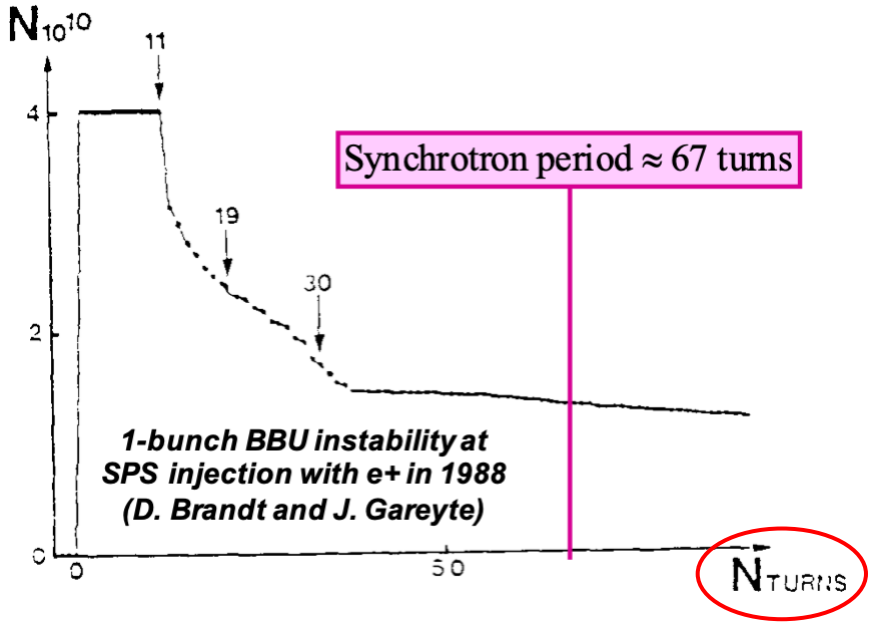

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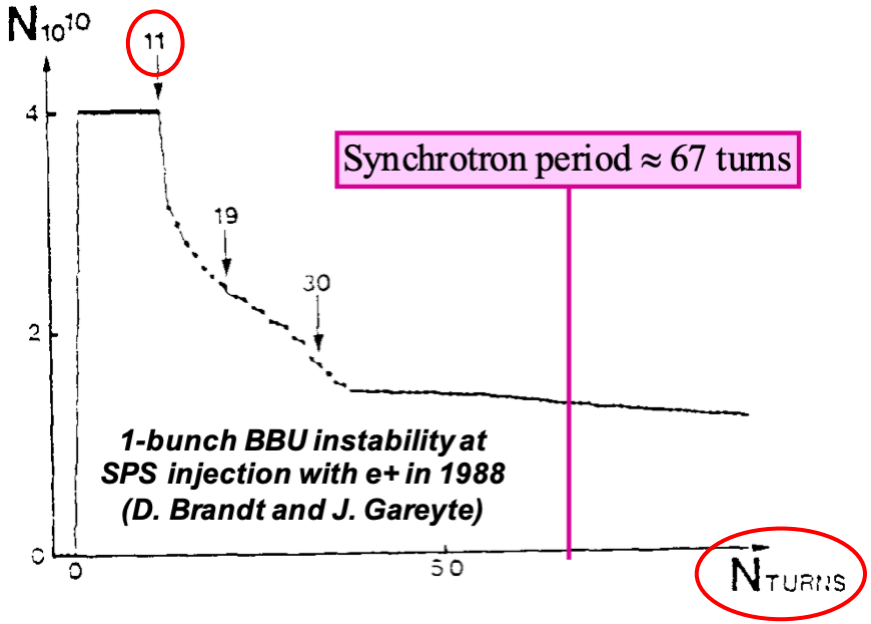

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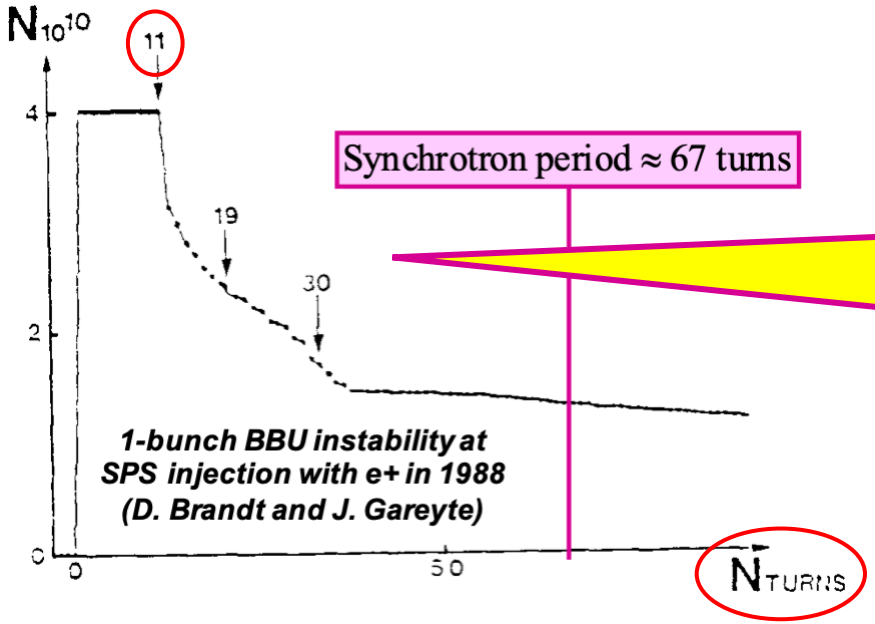


Even if everything needs to be done quickly with muons (due to short lifetime), many issues can happen with high bunch charges and high impedances (which is the case) => Need to be carefully studied!

Quite some challenging and interesting work ahead of us!

International MUON Collider Collaboration

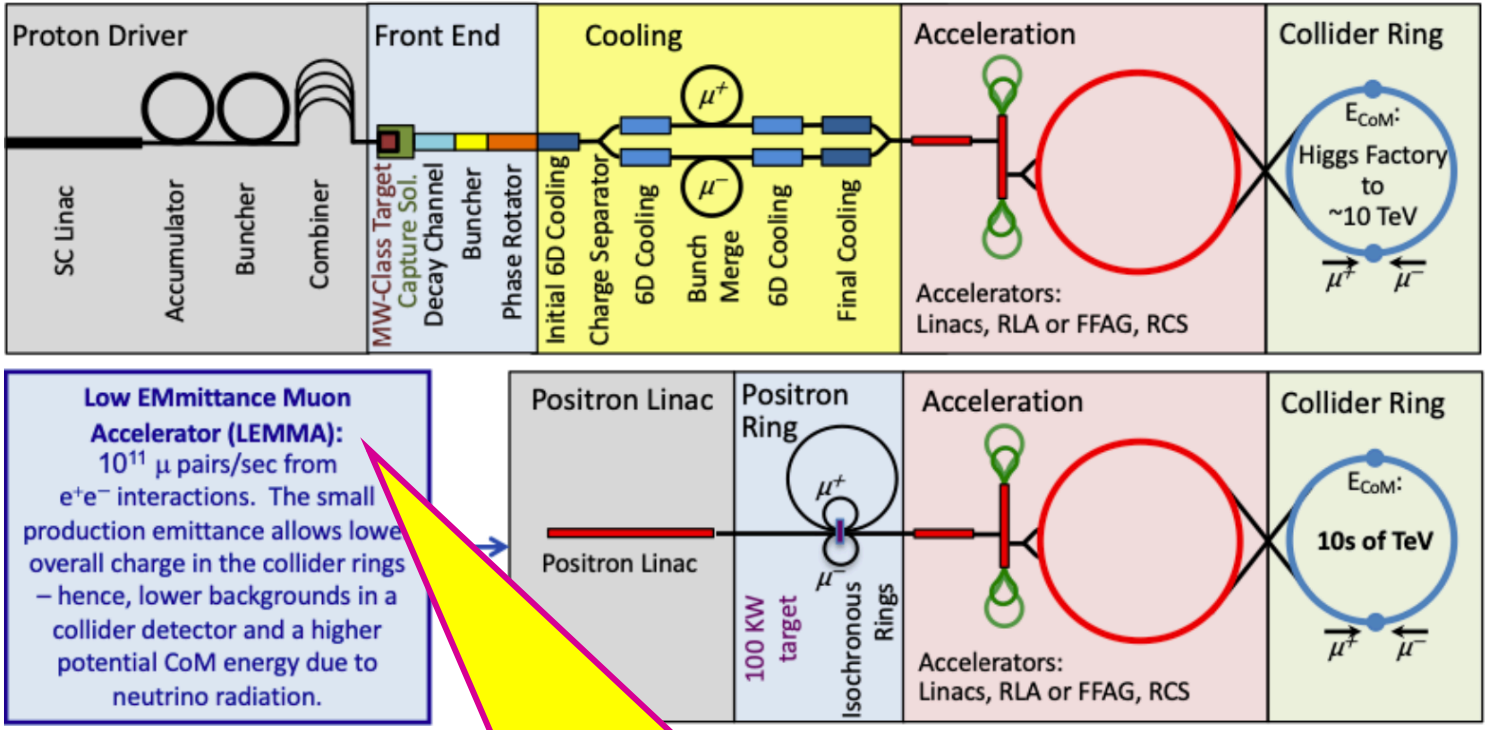
CERN

Thank you for your attention

International MUON Collider Collaboration

APPENDIX

International MUON Collider Collaboration



Not enough muons / low emittance on paper to be considered (for the moment) as a possible scheme for a muon collider

International MUON Collider Collaboration

LEMMA Muon Accumulator

Muon Collider Design Meeting
Beam dynamics meeting #7

2021/june/16, CERN online

Oscar Roberto BLANCO GARCIA
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INFN LNF
Istituto Nazionale di Fisica Nucleare

1

Main Messages

LEMMA stands for Low EMittance Muon Accelerator

1) LEMMA targeted a normalized emittance of **~0.040 µm.rad at 22 GeV**
   In simulations we have obtained **~5 µm.rad**
   Limited by the smallest ß*= 20 cm at the target, achieved with 500 T/m quads

2) LEMMA targeted a muon population of **10^{10} µ±** from 10^{16} e^+/s.
   In simulations we have obtained :
   - ~ **10^9** $\mu^\pm$, (Pantaleo's et al. Accumulator)
   - ~ **10^7** $\mu^\pm$, (Blanco's accumulator)

   Due to the emittance limitations we need to raise the positron rate

3) LEMMA combines three beams ($e+$, μ^+, μ^-) within a small 3D-space.
   The positron bunches have a population of ~ 10^{12} e^+.
   The effect of a growing (0 to 10^9) muon population in the same 3D-space of a high intensity positron beam has not been yet studied.

2

https://indico.cern.ch/event/1046241/contributions/4402862/attachments/2264435/3844471/BLANCO2021jun16.pdf